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# High speed electrical transmission line design and characterization

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ABSTRACT: High Energy Physics (HEP) experiments have unique requirements for data communication. High data speeds, combined with extreme restrictions on materials allowed, leads to custom transmission lines. This paper will present transmission line design theory, simulation and testing methods. Transmission line designs options like flexes and rigid PCBs as well as cables will be studied. Finite Element Analysis (FEA) software packages simulate energy dissipation and quality of transmitted signals. The characterisation techniques of time-domain reflectometry and frequency-domain measurements are discussed and compared. Bit-error-rate testing is presented and its limitations for design discussed. Methods to improve quality, like three different types of equalization are described.

KEYWORDS: Data acquisition circuits; Data Handling; Digital signal processing (DSP); Special cables

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## Contents



# 1 Introduction

Vertexing and tracking subdetectors for High Energy Physics (HEP) experiments deliver very high data rates, requiring multi-gigabits transmission links.

Commercial solutions for handling these high date rates are optical transmission or thick wire cables. However due to high radiation environments and low radiation length requirements in HEP experiments, electrical transmission with low mass custom designs are needed. Therefore, as the amount of material is a very important constraint, its minimization is a design challenge to overcome for transmission line design for HEP purposes. Optical data transmission is possible in HEP experiments when space and radiation limits allow, which precludes use in the ATLAS silicon pixel detector.

This paper will focus on the design, simulation, characterisation and test of flex transmission lines, whose results can be extrapolated to PCB transmission line designs and wire cables. Examples of transmission lines that are currently being used for both LHCb [1, 2] and ATLAS [3] upgrades will be presented and analyzed.



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### 1.1 Transmission line distortions

A differential transmission line can be defined as a pair of electrical conductors carrying an electrical signal from one place to another, see chapter 7 of ref. [4]. The two conductors have an inductance and capacitance per unit length, which can be calculated from their size, shape and the dielectric constant of the insulating material. Considering these factors there are four main types of losses that govern the propagation of waves through transmission lines. Radiative losses occur when the transmission line acts as an antenna due to the small separation distance between the conductors in comparison to the signal wavelength. This results in energy loss via radiation. The radiative losses increase linearly with signal frequency and can be controlled by appropriate conductor shielding. The second type are resistive and dielectric losses, the energy of the transmitted wave is dissipated due to the conduction resistance in the conductors and to molecular excitation of the dielectric material used as isolating material. Resistive losses can be controlled by using low resistivity conductors with low surface roughness and low loss dielectrics. Cross-talk, the third type of losses, takes place when a transmission line collects energy via radiation from neighboring conductors. This effect can be minimized by using guard traces, which are traces installed parallel to an existing high-speed signal line to isolate it. Finally reflection is a phenomenon that happens when the line impedance does not match the load impedance thereby a fraction of the signal returns to the source. Reflections can be prevented by controlling the geometry and the dielectric of the transmission line to achieve matching of the transmission line and load impedances.

## 2 Transmission line design

For the optimized transmission line design all the distortions described in the section above must be minimized so that the quality of the signal at the receiver allows data recovery within the error rate specification.

### 2.1 PCB and cable layout and routing basics

For a differential line design in a flex or rigid PCB there are some basic rules to follow in order to achieve optimum data transmission [5]. The first design rule is to use tightly coupled differential lines, which helps maintain balance within the differential pair and ensures that stray inductance is coupled equally on each conductor within the pair. Furthermore, tightly coupled differential pairs diminish EMI susceptibility (radiative losses). Secondly it is also critical to match the trace lengths of a given differential pair. Any propagation delay difference (skew) between signals of a differential pair will result in mode conversion between differential and common mode. These two modes have different propagation constants that will result in signal distortion at the far end.

High-speed signals should be routed over a solid GND reference plane and not across a plane split or a void in the reference plane unless absolutely necessary. Routing across a plane split or a void forces return high-frequency current to flow around the split or void. This can result in the following conditions: excess radiated emissions from an unbalanced current flow, delays in signal propagation due to increased series inductance, interference with adjacent signals and degraded signal integrity (that is, more jitter and reduced signal amplitude). A via presents a short section of change in geometry to a trace and can appear as a capacitive and/or an inductive discontinuity.

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These discontinuities result in reflections and some degradation of a signal as it travels through the via. Reducing the overall via stub length minimises the negative impacts of vias (and associated via stubs). Finally using guard/ground traces between each differential pairs will reduce the crosstalk between them.

The signal quality at the receiver can deteriorate due to the skin effect and dielectric losses. The skin effect increases resistive losses as it reduces the effective cross-section of the conductor for high-speed signal transmission. The skin depth is given by the following equation:

$$\delta = \sqrt{\frac{1}{\pi f \mu_0 \sigma}}$$

Where $\delta$ is the skin-depth in metres, $f$ is the frequency in Hz, $\mu_0$ is the permeability of free space ($4\pi \times 10^{-7}$ N/A$^2$) and $\sigma$ is the conductivity in S/m (for annealed copper $5.80 \times 10^7$ S/m). Dielectric losses are due to the varying electric field from the signal causing small realignment of weakly bonded molecules in the dielectrics around the signal conductors, which lead to heating of the material. It is proportional to the signal frequency. The oscillating field drives charge in the bond back and forth between two alternative configurations. This charge-motion gives rise to an electric current that, if there were no losses, would be $90^o$ out of phase with the voltage. In real dielectrics this current dissipates energy, just as a current in a resistor does, giving it a small phase shift, $\delta$ and this phase shift is known as loss tangent.

Choosing the appropriate materials for dielectrics, conductors and shielding according to the purposes of the circuit is a key point. Another outstanding factor to consider is the roughness of the signal conductor because a rougher surface increases the signal loss as frequency increases. As a use case for HEP experiment it can be pointed out that Teflon is one of the best materials as it has one of the lowest loss tangents although it is not radiation hard. Silver also has one of the smoothest surfaces but it activates causing background radiation so it cannot be used.

### 2.2 Impedance matching

As important as doing a good transmission line design and avoiding resistive losses is matching the impedance of the line to the rest of the system to avoid reflections. This is achieved by optimizing the transmission line geometry and dielectric materials used. The typical impedances are 50 ohms for single ended and 100 ohms for differential lines. There are tools based on standard electromagnetic equations to calculate an approximate value of the impedance. The accuracy of these tools is limited as the equations are simplified and do not include parameters like adhesives or roughness of the copper.

## 3 Characterization techniques

Any point to point transmission line can be evaluated with a port topology, see chapter 12 of ref. [4]. A simple transmission line, as the device under test (DUT) is described by a 4-port topology, as shown in figure 1.

The S-parameter is defined as the response divided by signal, $\S_{ij} \frac{b_j}{a_i}$, where $a_i$ is the incident power wave into port i and $b_j$ is the reflected or transmitted power wave on port j. For an RF signal


**Figure 1**. Differential scattering matrix.

incident on one port, some fraction of that signal gets reflected back out of the incident port, the remainder enters the port and then exits at (or scatters to) some or all of the other ports.

In order to carry out S-parameters measurements a vector network analyser (VNA) is required. Performing a good calibration of the VNA before taking a measurement is necessary to obtain accurate results. Time domain parameters can be derived from an inverse Fourier transformation of the s-parameters.

Furthermore, the DUT impedance should match the impedance of the VNA ports so there are no additional impedance mismatches.

Eventually, a DUT can be characterized with the Bit Error Rate (BER), number of errors in the recovered data per unit time. Nevertheless as it is necessary to have all the devices included in the communication chain and for the examples presented this was not the case these tests will not be included.

## 4 Examples of transmission line designs and characterization

In this section, some transmission line designs are presented.

### 4.1 ATLAS ITK pixel endcap ring tape

The first prototype of the ATLAS ITk pixel endcap ring tape is basically a curved bus tape that carries data to the “End of Stave” (EoS) where it is collected by a GBTx [6]. The design was not optimized for high speed data transmission, as it was not a requirement at design time. Nevertheless the design can be used to learn practices that need to be avoided whilst designing for high speed transmission.

The designed geometry, trace width, spacing and material choices do not result in the desired 100 ohms impedance. Additionally, the signal traces do not have a continuous reference. As it can be seen in figure 2 the differential signals cross over different ground or power planes (indicated in blue) or areas without any ground reference (indicated in black). Therefore in this design there is no dedicated return path.

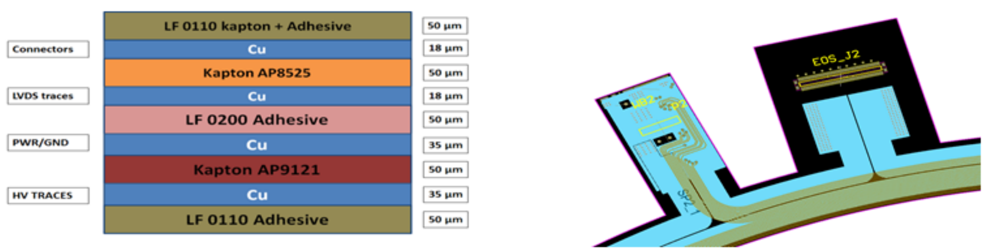


**Figure 2**. Layer stack of the ATLAS Rint Tape (left) and LVDS and power layers layout (right).

The lack of impedance matching, the impedance was measured to be 70, ohms results in a large signal reflection. The S-parameter SDD12 (measurement of transmitted voltage into port 1 while sending voltage in port 2), which characterises the transmission through the line, shown in figure 3 has peaks where the signal is completely attenuated at 1.6 GHz and 5 GHz which are due to the discontinuities in the reference plane. Furthermore the overall losses are very high.

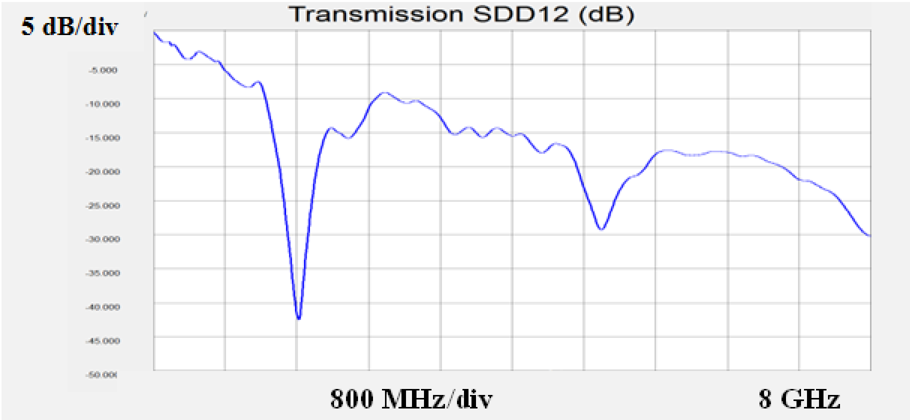


**Figure 3**. Transmission curve of the ATLAS ring tape.

### 4.2 LHCb tape

The LHCb Velo upgrade data transmission tape was designed with the following criteria: 56 cm long, data transmission rate of 5.12 Gbps with differential signalling and mechanical flexibility. Its functionality is to carry data from the LHCb upgrade VELO modules to the vacuum interface [7]. Concerning design characteristics, it has 0.2 mm trace width and spacing and 100 ohms differential impedance.

In order to achieve good signal integrity the design included the following features:

- Traces embedded in between two ground planes.
- Every LVDS pair is separated by two ground traces on the signal layers.
- Connectors sitting in the signal layer.
- Vias on the signal lines are avoided by placing the connector on the signal layer, by opening a window in the top layer.
- Stitching vias help in tightly couple the grounds on the three planes and provide a short signal return path.

The materials also were chosen to minimize losses. The dielectric is Dupont Pyralux AP8575 which has a low loss tangent and a conductor processed to have a very smooth surface to minimise the loss from the skin effect. The impedance value given by the online tool [8] is 90 ohms but this is not accurate since it does not take into account the glue layer. Observing figure 5, the value of the measured impedance is 115 ohms and the slope (see green section in the right hand plot) is due to



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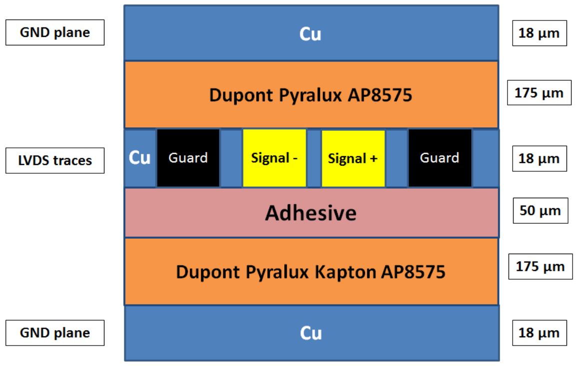


**Figure 4**. Layer stack of the LHCB tape.

the DC resistance of the traces. As the 100 ohms impedance was not achieved the design has been iterated. Lastly the transmission results are presented (left hand plot). It can be noted from this measurement that the transmission curve is very smooth compared to the one shown in figure 3. The loss at the Nyquist frequency 2.5 GHz for a 5 Gbps data rate is 7.37 dB. The bumps are introduced by connectors, see chapter 9 of ref. [5], which are always a point of impedance discontinuity (see purple colour of the right plot) whose pattern can be observed in all the plots included. To conclude the losses are low and it has very good impedance matching to the tester.

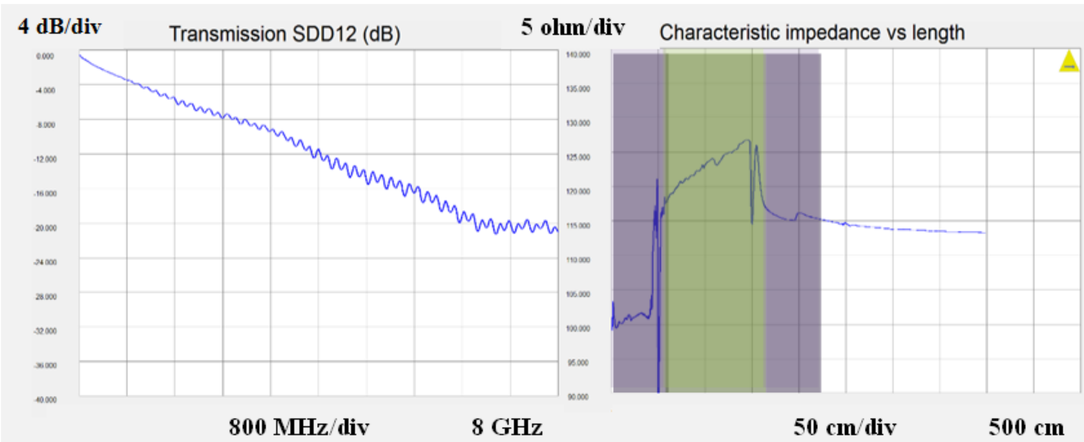


**Figure 5**. Transmission and time domain analysis for the LHCB tape.

### 4.3 ATLAS cables

As has been shown in the subsection 4.1, the ATLAS Ring Tape wasn't suitable for high speed data transmission so instead it was decided to design a cable that will transmit data at speeds between 2.5 and 5 Gbps directly from the module to the electrical to optical conversion circuitry outside of the high radiation area of the ATLAS inner tracker. A custom twisted pair cable with 36 AWG (American Wire Gauge of 0.127 mm diameter) was designed to perform this task.

Each conductor is a 7 strand Copper wire insulated with PEEK (colorless organic thermoplastic polymer, Poly-Ether-Ether-Ketone). The insulators on each conductor have measured thicknesses of 390 µm and 307 µm as they are custom designed. The twisted pair of conductors are shielded

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with 10 $\mu$m aluminum foil backed with 25um thick Kapton insulator in a spiral wrap. The cable has a design differential impedance of 100 ohm.

The S-parameter results from a 3 meters cable give a 8.66 dB transmission attenuation at 1.25 GHz and 13.4 dB attenuation at 2.5 GHz which are the Nyquist frequencies for data rates of 2.5 and 5 Gbps, see figure 6. The impedance increases over the length of the cable due to its DC resistance and has a value of 115 ohms (green section). Connectors can as well be observed (purple). The transmission attenuation is reasonable for such a long cable at these given frequencies and the measured impedance is close to the design values.

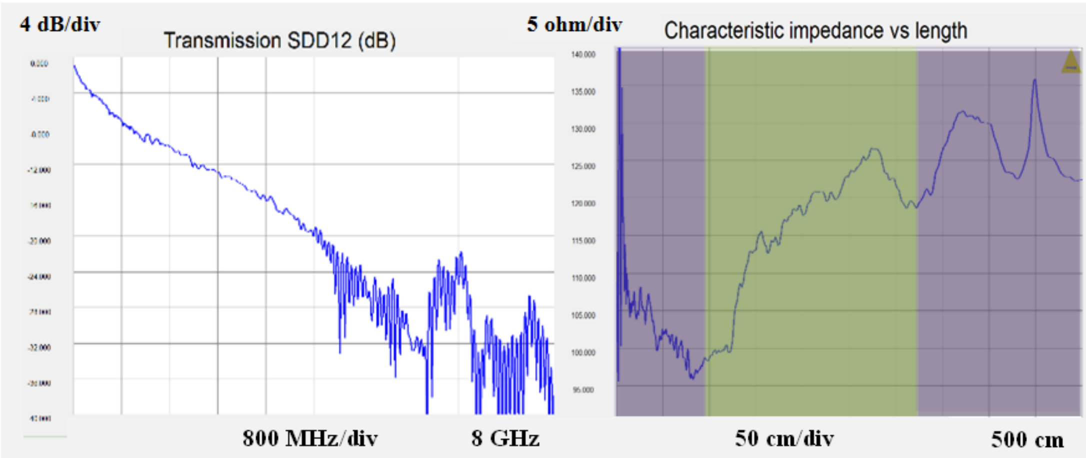


**Figure 6**. Transmission and time domain for the ATLAS cables.

## 5 Simulations

Simulations based on a simplified tape design were used to investigate phenomenological dielectric behaviour of alternative cable variations. Simulations were performed using ANSYS Electronics Desktop. A simple 2-dimensional twinax tape geometry was defined with 2 differential copper conductors covered with PEEK dielectric and enclosed in air with an aluminum shield as reference ground (figure). The cable parameters were set to 1m with differential impedance $Z = 100\,\Omega$. No frequency dependence was included for the dielectric material. A wide frequency sweep of 10MHz-10GHz, with 10MHz, was used, with a relatively coarse mesh to limit calculation time.

A comparative study of the skin effect with various conductor thicknesses was done. Various conductor core radii were simulated: 80, 130, 180, 230 $\mu$m. Signal transmission was found to drop as frequency increases due to charge concentration on the conductor surface. Larger radii conductors with relatively large circumference perform better across the frequency range, since charge concentration is less pronounced.

Three geometry variations were studied to investigate the effects of multiple conducting cores (with constant area): 1, 3 and 6 cores per conducting line. Two processes resulting from the skin effect convolute. Firstly, there is attraction across the differential pair due to the relative phase of the signal. Secondly, within each signal line, there is a repulsive effect between cores as each have like charges concentrating on the surface. The overall effect is for the charge to redistribute across the cores in such a way as to preserve signalling properties. Figure 7 shows the reflection (S11) and transmission (S21) scattering parameters of the three variations across the frequency range in dB.



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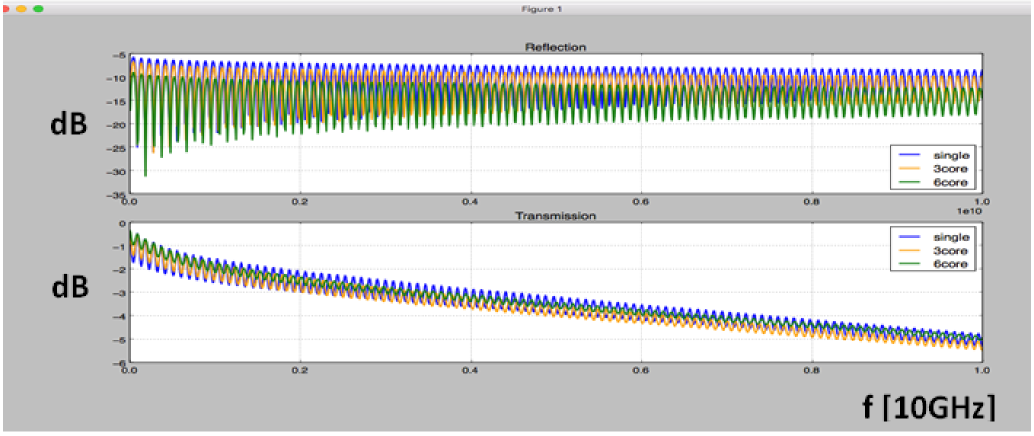


**Figure 7**. Simulation of reflections and transmission for single and multi-core cables.

# 6 Equalization

Considering a given transmission system formed by transmitter, transmission line and receiver, there will always be signal degradation. However, it is necessary to make sure that such degradation is low enough that the receiver will be able to take the right decision and decode the symbol correctly. There are several techniques that can be applied at different points in the chain that will help to improve the signal and therefore aid the receiver in reading out the correct data.

## 6.1 Equalization techniques

Equalisation can be made at the sender side with pre-emphasis or at the receiver side with FFE, DFE or CTLE. In this paper only equalisation on the receiver side will be discussed. Equalization provides functionality in the receiver to help overcome the high-frequency signal losses of the transmission line.

There are a wide variety of equalizers that can be used, and the following section introduces the common types:

- *Feed-Forward-Equalization (FFE)*: corrects the received waveform with information about the waveform itself and not information about the logical decisions made on the waveform. It acts like a FIR (finite impulse response) filter and uses the voltage levels of the received waveform associated with previous and current bits to correct the voltage level of the current bit, see figure 8. It modifies the amplitudes of symbols surrounding transitions while keeping the transmitted power constant.

- *Continuous Time Linear Equalization (CTLE)*: it is a linear filter applied at the receiver that attenuates low-frequency signal components if it is passive and apart from that it amplifies components around the Nyquist frequency[1] when active. Passive R-C (or L) can implement high-pass transfer function to compensate for channel loss. It cancels both precursors and long tail interference intersymbol which is a distortion of a signal in which one symbol

[1]http://www.edn.com/electronics-blogs/all-aboard-/4430181/What-is-the-bandwidth-of-a-high-speed-serial-link-signal–Rule-of-Thumb–11.

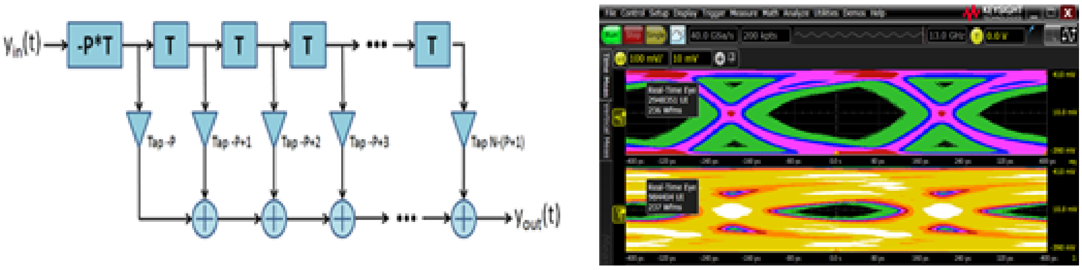


**Figure 8**. Decision diagram and eye-diagram after and before FFE.

interferes with subsequent symbols. It can be purely passive or combined with an amplifier to provide gain.

It is a completely analogue filter. Therefore, the values of the resistors and capacitors can be calculated accurately using simulation programs such as Spice or Cadence if the frequencies that are going to be attenuated or boosted are known. Furthermore, the gain of the transistors should be chosen according to the desirable filter behavior. The CTLE which was simulated for both ATLAS and LHCb upgrade can be found in figure 9.

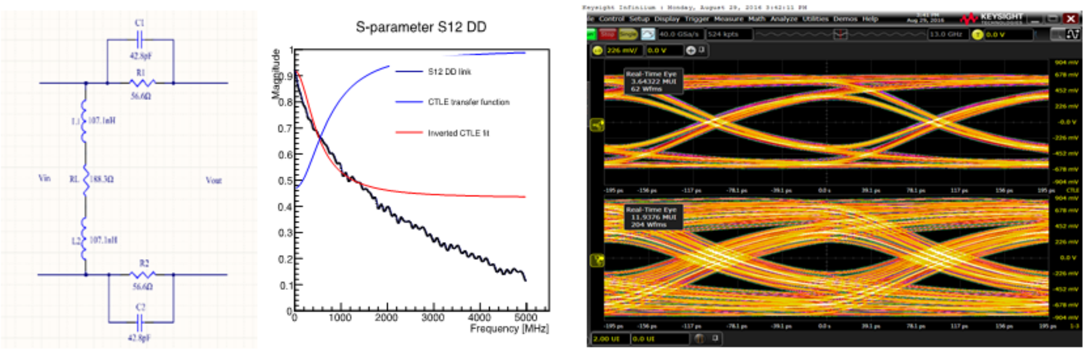


**Figure 9**. CTLE filter, how to implement it and eye-diagram after and before.

- *Decision Feedback Equalization (DFE)*: it is a non-linear equalizer. A slicer makes a symbol decision, i.e. quantizes input. The ISI is then directly subtracted from the incoming signal via a feedback FIR filter.

  Looking carefully at this diagram, it can be appreciated that this type of equalization has similarities with the FFE. The way of calculating the tap values are very similar. First you have to calculate from the transmission parameters the impulse response of the cable. Then sample it at the right rate and get the post cursors values in order to determine the FIR filter. Its mathematical implementation is shown in figure 10.

## 7 Conclusions

In summary, it can be said that transmission lines for high-speed applications require a very careful design. The main parameters to consider while designing a transmission line are:

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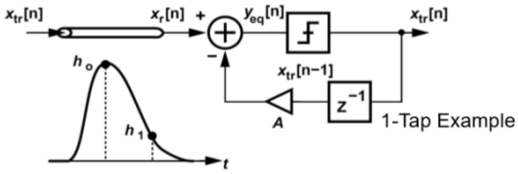


$$
\begin{aligned}
x_r[n] &= h_o x_{tr}[n] + h_1 x_{tr}[n-1] \\
y_{eq}[n] &= x_r[n] - A x_{tr}[n-1] \\
&= h_o x_{tr}[n] + \cancel{h_1 x_{tr}[n-1]} - \cancel{A x_{tr}[n-1]}
\end{aligned}
$$

**Figure 10**. DFE equation and diagram.

- Material choice → In order to avoid skin effect and dielectric losses as well as matching the impedance.
- Geometry of the design → PCBs (stripline, microstrip etc.) or cable.
- Recovering performance → Equalization techniques.

In order to be able to fully characterize a transmission line in the measurements should be included the whole chain: transmitter plus channel (tapes and cables) and receiver.

The minimisation of the number of connectors improves the signal quality as there are fewer reflections due to impedance mismatches.

Designing a transmission line with low material requirements for high energy physics experiments has proven to be a very difficult task. The next step is determine the BER but this requires the full system to be in place to make a meaningful measurement.

## Acknowledgments

This work was supported by Giorgos Sidiropoulos and Stephan Eisenhardt who designed the ATLAS ITk Pixel Endcap Ring Tape in the University of Edinburgh as well as by Martin Kocian from SLAC and Jason Nielsen from the University of California Santa Cruz who provided the cables studied.

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